Induced Cooperative Multi-user Diversity Relaying for Multi-hop Cellular Networks

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Abstract— **In this paper we study the multi-user diversity gain in the downlink of single-hop and multi-hop infrastructure-based networks. We propose a base-station coordinated cooperative relaying method, Cooperative Induced Multi-user Diversity Relaying (CIMDR), to overcome the fundamental limitations on the average achieved net throughput per-user. In the proposed method, multi-user diversity is induced and then exploited in a 2-hop relaying scheme to improve per user achieved data throughput. We show that by using the proposed method, the throughput per-user and the packet-drop-ratio are significantly improved.**

I. INTRODUCTION

In wireless cellular networks with multiple users, *multi-user diversity* is achieved as a result of having independent time-varying wireless channels between the base-station and different users in the coverage area. The multi-user diversity gain arises from the fact that, in a system with many users whose channels vary independently, there is likely to be a user with a “very good” channel at any time. System throughput is then maximized by allocating the shared radio resource at any time to the user that can best exploit it [1], [2], [3]. This approach has been employed in high-speed downlink standards for the third generation (3G) cellular wireless communications standards, HSDPA and 1xEV-DV.

For Beyond-3G wireless communication systems, multi-hop deployment has been widely considered as an augmenting option to single-hop transmission [4], [5]. In multi-hop cellular networks, the data-units are transmitted to the destination through relays. Such deployment concept deems to be a promising combination of the dynamics of mobile ad-hoc networks and the reliability of cellular networks.

To exploit the multi-user diversity in a multi-hop network, a relaying method is proposed in [6], in which multi-user diversity is exploited in each hop by selecting the next relay based on the instantaneous channel quality. However, the transmission to only one relay reduces the opportunity of finding a good channel in the next hop.

In this paper, we study the multi-user diversity gain in single-hop and multi-hop cellular networks. We obtain an upper-bound on the achievable average throughput per-user in a cellular data network in which multi-user diversity scheduling [3] is utilized. The derived upper-bound is a function of the number of users in the cell coverage area, base-station maximum transmit power, maximum supported transmit bit-rate, and average maximum channel gain. To improve achievable average throughput per-user, this paper proposes a base-station coordinated cooperative relaying scheme, namely *Cooperative Induced Multi-User Diversity Relaying* (CIMDR), which uses the broadcast feature of the wireless channel to induce multi-user diversity through a two-pase relaying process. We show that by using the proposed method, the throughput per-user and the packet-drop-ratio are significantly improved.

II. SYSTEM MODEL

We consider an infrastructure-based wireless network in which base-stations with a maximum transmit power level of P_{max} are located at the center of their coverage area. An access-point transmits a signalling channel that can be received by all users in the coverage area.

In our modelling, there are n mobile users, indexed by i, distributed uniformly in the coverage area. Each packet has a large delay tolerance and includes the identity (e.g., physical address) of the destination user. The wireless channel gain between the access-point and ith user at time t is given by the process $\{g_i(t)\}$ which is assumed to be stationary and ergodic. Moreover, for different users in the coverage area, the corresponding channel processes are assumed to be independent and identically distributed (i.i.d.).

At any time t, a resource allocation policy, $\mathcal{P}$, coordinates the data transmissions from the access-point to relays, or relays to destination users. For a resource allocation policy, $\Gamma_i^{\mathcal{P}}(t)$ is defined as the *achieved downlink throughput of user i at time t*, that is the number of bits received by user i at time t. For a resource allocation policy, we define *the feasible long-term achieved downlink throughput per-user*, $\Gamma^{\mathcal{P}}(n)$, such that

$$\lim_{T\to\infty} \inf_i \frac{1}{T}\sum_{t=1}^{T} \Gamma_i^{\mathcal{P}_{\mathcal{D}}}(t) = \Gamma^{\mathcal{P}_{\mathcal{D}}}(n). \tag{1}$$

$\Gamma^{\mathcal{P}}(n)$ depends on various factors including the maximum supported bit-rate, number of users in the coverage area, and the wireless channel temporal characteristics. The definition in (1) is similar to that presented in [7], for ad-hoc networks.

III. MULTI-USER DIVERSITY

To exploit multi-user diversity, a resource allocation policy, $\mathcal{P}_{\mathcal{D}}$, is employed. This policy, in its simplest form, allocates the maximum access-point transmit bit-rate to a user i^* at each time t, where

$$i^*(t) = \arg\max\{g_i(t)\}. \tag{2}$$

Note that, selecting $i^*(t)$ based on the channel condition may result in an unfair resource allocation. To resolve the fairness issue, some corrective scheduling methods are often used (see e.g., [3], [8], [9]). Since our focus is on the multi-user diversity gain, we simply consider a long-term fairness requirement in which $\lim_{T\rightarrow\infty}\sup_{i,j}\frac{1}{T}\sum_{t=1}^{T}\left|\Gamma_i^{\mathcal{P}}(t)-\Gamma_j^{\mathcal{P}}(t)\right| = 0$; that is a direct consequence of the i.i.d. wireless channels between different users in the coverage area and the base-station.

Note that, in order to exploit multi-user diversity, according to $\mathcal{P_D}$, a user's packets have to be delayed until the channel becomes the best relative to other users. Therefore, the time-scale of channel variations that can be exploited by $\mathcal{P_D}$ is limited by the delay tolerance of the corresponding application.

It is shown that for the above mentioned resource allocation policy, $\mathcal{P_D}$, the overall system throughput performance is significantly higher than that of simultaneous transmission [1], [3], [10]. The greater the number of users in the coverage area, the higher is the probability of occurrence of a good channel, which results in a greater improvement in the access-point throughput. However, the achieved downlink throughput per-user is still limited by the maximum transmission bit-rate and coverage area, thus limited by fundamental architectural constraints.

Consider a CDMA-based radio interface; for transmission with a rate $R_i(t)$ bits/s to a user i, the basic bit-energy to the interference-plus-noise spectral density constraint should be satisfied. Thus

$$\frac{W}{R_i(t)}\frac{P_{max}g_i(t)}{I_0} \geq \rho_i(t), \tag{3}$$

where I_0 is the interference-plus-noise power, W is the chip rate and $\rho_i(t)$ is the minimum required bit-energy to the interference-plus-noise spectral density for the data transmission with bit-rate $R_i(t)$. For a user i selected for transmission, using (3) we write,

$$R_i(t) \leq \xi_0 g_i(t) \tag{4}$$

where $\xi_0 = \big(\rho_i(t)I_0\big)^{-1}WP_{max}$.

Proposition 1: For large number of users in the coverage area, the feasible long-term achieved downlink throughput per-user, $\Gamma^{\mathcal{P_D}}(n)$, is upper-bounded by

$$\frac{\xi_0}{n}\lim_{T\rightarrow\infty}\inf_{i}\frac{1}{T}\sum_{t=1}^{T}g_{i^*}(t),$$

where $i^*(t)$ is given by (2).

Proof: We have

$$\lim_{T\rightarrow\infty}\inf_{i}\frac{1}{T}\sum_{t=1}^{T}\Gamma_i^{\mathcal{P_D}}(t) = \lim_{T\rightarrow\infty}\inf_{i}\frac{1}{T}\sum_{t=1}^{T}a_i(t)R_i(t) \tag{5}$$

where $a_i(t)$ is the selection indicator; i.e., $a_i(t) = 1$, if user i is selected for transmission at time t, and 0 otherwise. Summing (5) over all users, we have

$$\begin{aligned}\Gamma^{\mathcal{P_D}}(n) &\leq \frac{\xi_0}{n}\lim_{T\rightarrow\infty}\inf_{i}\frac{1}{T}\sum_{i=1}^{n}\sum_{t=1}^{T}a_i(t)g_i(t) && (6)\\ &= \frac{\xi_0}{n}\lim_{T\rightarrow\infty}\inf_{i}\frac{1}{T}\sum_{t=1}^{T}g_{i^*}(t) && (7)\end{aligned}$$

which complete the proof. ■

Proposition 1 shows that the downlink throughput per-user is upper-bounded by $g_{i^*}(t)$. To increase multi-user diversity gain, in [3], multiple transmit antennas are used to induce large and fast channel fluctuations, i.e., greater $g_{i^*}(t)$. Also in a multiple-cell scenario, the independent time variations of the wireless channels between a user and the neighboring access-points is introduced in [11], [12], as a new dimension in multi-user diversity. This form of diversity is exploited by joint access-point assignment and packet scheduling, which results in greater $g_{i^*}(t)$ and thus greater multi-user diversity gain per-user.

To exploit the multi-user diversity in a multi-hop network, a relaying method is proposed in [6]. In this method, using a sequential optimization approach, multi-user diversity is exploited in each hop by selecting the next relay based on the instantaneous channel quality. However, selecting only one relay reduces the opportunity of capturing a good channel in the next hop. In the following section, we propose an base-station coordinated cooperative relaying method, which exploit multi-user diversity in multi-hop cellular networks.

IV. COOPERATIVE INDUCED MULTI-USER DIVERSITY RELAYING

Cooperative Induced Multi-user Diversity Relaying (CIMDR) (Fig.1) exploits the broadcast nature of wireless channel to induce multi-user diversity through a two-phase process. In the first phase, access-point broadcasts data packets with its maximum bit-rate. Some users in the coverage area are likely to receive the transmitted data packets. These users, act as potential relays in the second phase; each potential relay wait until the occurrence of a "good channel" to the destination user and then transmit the data packets. As soon as the transmission is carried out by one of the potential relays, the access-point manages to release the packets saved buffered in other potential relays.

We consider a 2-hop infrastructure-based network. Access-point is located at the center of the coverage area and its maximum transmit power is P_{max}. Packets can be transmitted directly from the access-point to the users, or they can go through another mobile user serving as a relay. Access-point transmits signalling on dedicated control channel(s) that can be received by all users in the coverage area.

There are n mobile users, indexed by i, distributed uniformly in the coverage area. Mobile users are able to receive, temporarily save and relay packets in the same frequency band of access-point transmission. They also transmit signaling information on an uplink signaling channel. Mobile terminals have a large enough buffer to store relay packets. Each packet

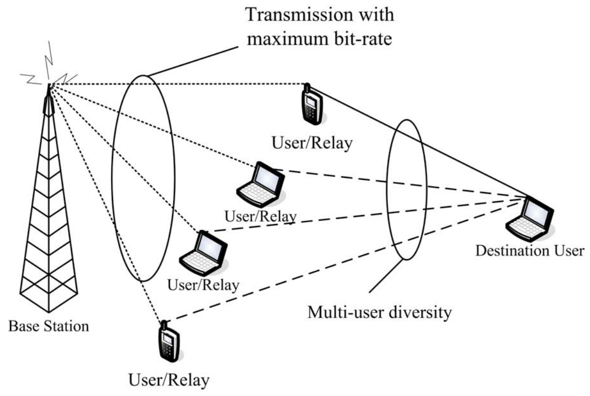

Fig. 1. CIMDR.

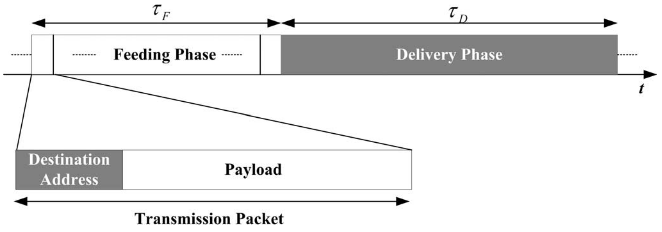

Fig. 2. CIMDR two-phase protocol and packet structure.

has a large delay tolerance and includes the identity (e.g., physical address) of the destination user. Each user in the coverage area broadcasts a pilot signal to indicate its identity. This pilot signal is also utilized by the relays for channel estimation. To decrease power consumption, broadcasting of users' pilot channel can be activated upon receiving a signal (from the access-point) indicating the existence of a data packet destined to that mobile user.

Since by this scenario we *induce* multi-user diversity through generating independent paths between the destination user and m relays, we name it Cooperative Induced Multi-user Diversity Relaying (CIMDR).

A. CIMDR Protocol

The proposed scenario, $\mathcal{P}_{\mathcal{I}}$, has two phases: the *feeding phase* and the *delivery phase*. These two phases occur sequentially in time (Fig.2). The time-span of each phase (i.e., τ_F and τ_D) is assigned based on the network traffic and the communication environment characteristics. Fig.3 shows the signalling procedure of CIMDR protocol.

Feeding Phase: In the feeding phase, packets are broadcasted by the access-point with its maximum bit-rate; the total number of transmitted bits in the feeding phase would be $\tau_F.R_{max}$, where τ_F is the time duration of the feeding phase. During the feeding phase multiple packets are transmitted using time domain scheduling. Any user which receives a data packet in the feeding phase acts as potential relays in the delivery phase.

The transmission order of the queued packets in the access-point is managed by a higher-layer functionality. If the destination user is among those who receive packets in the feeding phase, it sends a received acknowledge signal, R-ACK, to the access-point. Consequently, the access-point broadcasts a data release signal, D-REL, and all other relays release that packet.

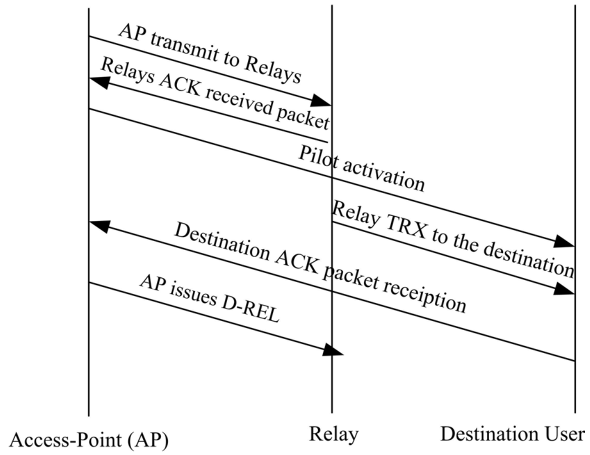

Fig. 3. CIMDR signaling: Normal transmission.

Here we assume that the number of users in the coverage area is high enough that in each time instant there is, at least, one user that can receive the transmitted data in the feeding phase. In cases where no mobile user in the coverage area can receive the transmitted packet in the feeding phase, the access-point should reduce its bit rate.

In the feeding phase, multi-user diversity gain comes from the fact that the access-point radio resource is only allocated for transmission with its maximum bit-rate. Note that for a large number of users in the coverage area, it is likely that some users will have a channel state that supports the access-point's highest bit-rate.

Delivery Phase: In the delivery phase, the access-point is kept inactive and only transmissions from relays to the final destinations are allowed. Each relay continuously tracks the quality of the wireless links to the neighboring users as well as their identity. If a relay is able to achieve a transmission bit-rate greater than or equal to a system parameter R_0 bits/s, then that relay transmits to the destination user. The selection of R_0 critically affects the system performance and is elaborated in the Proposition given below.

Medium access control can be either a contention-based method or an access-point coordinated non-contention based method. Upon successful transmission, destination user sends an R-ACK signal to the access-point. Consequently, the access-point broadcasts a D-REL signal and other relays release that packet. If the access-point does not receive an R-ACK corresponding to a packet in a predefined time interval, τ_{max} seconds, that packet is considered lost and a D-REL signal is broadcasted by the access-point. That packet may be considered for retransmission in a later time.

Multi-user diversity in the delivery phase is exploited by transmission on channels with the achieved bit-rate greater than or equal to R_0. Note that in practice the transmit bit-rate may be adjusted based on the channel status which is fed back into the access-point by the users.

B. *Incentive system for users' cooperation*

There should be an incentive system to provide reasonable motivation to the users for participation in CIMDR. The incentive problem is heavily studied in the context of mobile ad-hoc networks (see e.g., [13]). In an infrastructure-based multi-hop system it is possible to have a network-based incentive system which makes this problem a lot easier. Here, we propose a simple credit based incentive system.

In this system a user i is granted a *participation credit* of $\mu(t)$ upon participating in relaying process at time t. This is due to the fact that the mobile user allocates a part of its processing power for tracking the neighboring mobile stations and for involving in the corresponding signaling processes. As soon as finding the destination user and detecting a channel with available bit-rate greater than or equal to R_0, the relay transmits the data packet thus allocates a portion of its transmission power to relaying. In this case, the network grants a *relaying credit* of $\nu(t)$ to that mobile user. The values of $\mu(t)$ and $\nu(t)$ are related to the network charging strategy and can be varied in different times of the day based on the network traffic. In such a scenario with m mobile users participating in CIMDR, the total granted credit per packet transmission is $m.\mu(t) + \nu(t)$ which would be considered as part of the transmission cost for each data packet.

V. PERFORMANCE EVALUATION

For a given medium access control technique, $0 < \gamma \leq 1$ is defined as the medium access control gain, which shows the average portion of the radio resource (e.g., transmission time) that can be allocated to the competitors for a shared media. For non-contention based medium access control mechanisms $\gamma = 1$. Let R be the average access-point transmission bit-rate for single-hop transmission with multi-user scheduling. The following proposition provides the condition on the system parameters for CIMDR.

Proposition 2: For a large number of users in the coverage area, by using CIMDR the access-point throughput is increased compared to the single-hop transmission if

$$\frac{1}{R_0} < \gamma\Big(\frac{1}{R} - \frac{1}{R_{max}}\Big). \tag{8}$$

Proof: Let $\Phi_D(t)$ and $\Phi_F(t)$ be the indicator functions for delivery and feeding phases, respectively. Therefore, $\Phi_D(t) = 1$ ($\Phi_F(t) = 1$) when the system is in delivery (feeding) phases and $\Phi_D(t) = 0$ ($\Phi_F(t) = 0$), otherwise. The total data bits in the system at time t, $\Theta(t)$, can be calculated as

$$\Theta(t) = \int_0^t \Big(\gamma R_0 \Phi_D(\alpha) - R_{max}\Phi_F(\alpha)\Big) d\alpha.$$

For system stability, it is required that $\lim_{T\to\infty} \Theta(T) = 0$, thus

$$\tau_D \gamma R_0 = \tau_F R_{max}. \tag{9}$$

On the other hand, compared to the single-hop transmission, the total access-point throughput will be increased if

$$\tau_F R_{max} > (\tau_F + \tau_D) R. \tag{10}$$

Hence, using (9) and (10),

$$\frac{1}{R_0} < \gamma\Big(\frac{1}{R} - \frac{1}{R_{max}}\Big). \tag{11}$$

This proves the proposition. ■

On one hand, if R_{max} is very large, then a smaller number of users in the coverage area will receive the data packets in the feeding phase. On the other hand, decreasing R_{max} will increase the number of potential relays but will decrease the overall rate. The transmission rate R_{max} may also be adjusted based on the number of potential relays; if data packets are not received by a reasonable number of mobile users, then R_{max} may be decreased.

Given the condition in (8) holds, within the interval $[0,\ T]$ for $T \to \infty$ all packets transmitted to the relays will be delivered to the users. Therefore, for CIMDR, it is simple to show that (7) is modified as

$$\Gamma^{\mathcal{P}_\mathcal{I}}(n) \leq \frac{\xi_1}{n}\breve{g}, \tag{12}$$

where ξ_1 is defined similar to ξ_0 in (7) and $\breve{g}$ is the minimum time-average value of the channel gain between the access-point and the relay with the maximum transmission bit-rate. Note that

$$\lim_{T\to\infty} \inf_i \frac{1}{T}\sum_{t=1}^{T} g_{i^*}(t) < \breve{g}, \tag{13}$$

which is a direct consequence of smaller path-losses because of multi-hop transmission. This directly results in $\Gamma^{\mathcal{P}_\mathcal{I}}(n) > \Gamma^{\mathcal{P}_\mathcal{D}}(n)$. In other words, using CIMDR, the achieved average throughput per user is increased.

Note that τ_{max} has an important role in the performance of CIMDR. If $\tau_{max} \to \infty$, then a packet can be kept waiting in a potential relay until the occurrence of a very high rate channel (i.e., very large R_0). For moderate values of τ_{max}, the mobility is very important. The higher the users' mobility the higher is the probability of the occurrence of a high bit-rate channel in the second hop. For a given mobility profile, a larger value of τ_{max} results in the exploitation of the mobility in a more efficient way.

VI. SIMULATION RESULTS

We simulate a single-cell DS-CDMA system with n active users based on UMTS standard [14]. Users are uniformly distributed in the coverage area. The simulation parameters are presented in Table I. A simple mobility model has been implemented, in which at each time instant, a user randomly located within a circle with its previous location in the center and a diameter of 2.5 meters.

To show the effect of multi-user diversity, we consider three different systems: in System I, for each user the access-point transmits packets in first-come-first-serve fashion using a time domain scheduling scheme. In System II, packets are scheduled based on $\mathcal{P}_\mathcal{D}$. Transmission in System III is based on $\mathcal{P}_\mathcal{I}$, with a non-contention based medium access control technique in the delivery phase.

TABLE I

SIMULATION PARAMETERS.

Parameter	Value
Cell radius	100 m
Access-points transmit power	10 W
Standard dev. of log-normal fading	8 dB
Background noise density	-174.0 dBm/Hz
Propagation loss exponent	4
Time-slot length	10 ms
R_{max}	2 Mbps
R	384 Kbps
Medium access control gain (γ)	≈ 1
Minimum required E_b/I_0	2 dB

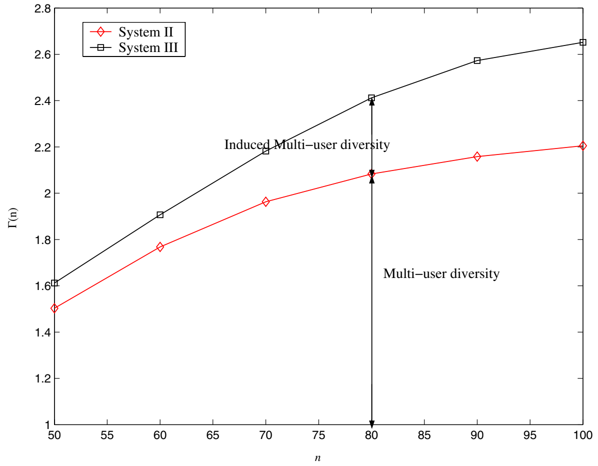

Fig. 4. Normalized average achieved net throughput vs. the number of users.

System I is considered as the benchmark, and the average achieved net throughput of Systems II and III are normalized by the average achieved net throughput of System I. Fig.4 illustrates the normalized average achieved net throughput versus the number of users in the coverage area for $\tau_{max} = 2$ s. The difference between the throughput gains of Systems II and III indicates the achieved multi-user diversity gain resulting from exploiting the induced multi-user diversity by CIMDR. As it is expected, this gain is increased by the number of users. Note that normalized throughput curve will saturate because of the access-point total throughput constraint.

We also compare the packet-drop-ratio for System II and System III. Packets are considered lost when they cannot be transmitted within a delay threshold of $\tau_{max} = 2$ s. As it can be seen in Fig.5, using CIMDR improves the packet-drop-ratio performance. The greater improvement in the packet drop ratio is archived by a larger number of users in the coverage area and a larger delay tolerance of 10 s.

VII. CONCLUSION

In this paper we study the multi-user diversity gain in the downlink of single-hop and multi-hop infrastructure-based networks. We proposed Cooperative Induced Multi-user Diversity Relaying (CIMDR) scheme to overcome the fundamental limitations on the average achieved net throughput per-user. In the proposed method, multi-user diversity is induced in a 2-hop forwarding scheme and then exploited to improve per user achieved data throughput. Simulation results confirm that by using the proposed method, the throughput per-user and the packet-drop-ratio are significantly improved.

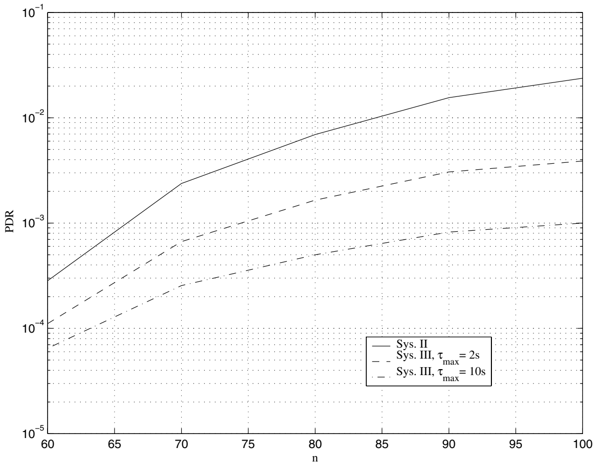

Fig. 5. Packet-drop-ratio (PDR) of CIMDR and single-hop multi-user diversity scheduling for $\tau_{max} = 2$ and 10 seconds.

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